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THE DESIGN OF THE REFERENCE ORBIT FOR NISAR, THE NASA-ISRO SYNTHETIC APERTURE RADAR MISSION

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The NISAR mission plans to use a 12-day-repeating sun-synchronous orbit for repeat-pass interferometry at multiple time scales using SAR data. For the interferometry to work the radar measurements must be made from within a critical baseline, which happens if all of the orbits are maintained to be within a fixed tube around a reference orbit. This paper describes the choice of dynamical models used in defining such a reference orbit, the perturbative effects of dynamics not considered in the repeat orbit, and the process of designing the orbit to repeat. We also describe our method for sharing the repeat orbit among multiple mission participants who use different models and software.

INTRODUCTION

The NISAR mission is currently being developed jointly by NASA and ISRO (the Indian Space Research Organisation) for a launch in 2021. It uses L-band and S-band radar instruments to generate synthetic-aperture radar images of the surface of the Earth and then uses interferometric techniques to combine the images to show changes as a function of time. By continually maintaining the orbit to stay close to a predefined reference orbit, interferometry can be applied to any pair of passes over a given point so that change can be measured over a variety of time scales. The requirements on the baseline between the repeat passes have been worked out[1] and the overall mission design to meet those requirements has been described in an earlier paper.[2]

Interferometric synthetic aperture radar (InSAR) from space

NISAR will not be the first space mission to take data to generate InSAR products, nor even the first to provide global InSAR images as one of its standard products. The first demonstration of InSAR from space was done in 1990 using data from the 1978 SEASAT mission; several SAR missions in the 1990s subsequently produced InSAR images, most notably the European ERS-1 mission. The first global InSAR coverage was the Shuttle Radar Topography Mission (SRTM), which used two radar antennae to generate InSAR images from a single pass. Later missions have used two spacecraft flying to the same reference orbit (the European TerraSAR-X and TANDEM-X missions, launched in 2007 and 2010 respectively) or one spacecraft making repeat passes near a reference orbit (the Japanese ALOS-2 mission, launched in 2014 and renamed Daichi 2).

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The reference orbit for TerraSAR-X[3] used a 120 x 120 gravity field for the Earth, the orientation of which was modeled in space including precession and nutation. After solving for orbit parameters to make the orbit sun-synchronous and frozen, the designers had difficulty getting the orbit to return to the same Earth-relative state at the end of the repeat cycle. They solved this difficulty by including maneuvers within the repeat-cycle boundaries, which were then minimized to values of a few centimeters per second, and the resulting orbit was saved in an ephemeris as the reference orbit. The reference orbit for ALOS-2[4] was designed the same process as TerraSAR-X.

Reference orbit considerations

Since the NISAR science is based on radar measurements of the ground, the requirements for the baseline of the repeated measurements are relative to the ground. Hence our requirements for controlling the orbits are ground-relative, i.e., we need to fly within a diamond-shaped tube around a reference orbit that is fixed relative to the ground.

Orbital dynamics are most simply expressed in inertial space, and our standard ephemeris format models orbits likewise, so our use of standard propagation software means that we generate high-precision approximations in inertial space of the actual orbit. In that context we can see two main ways in which the propagated orbit might deviate from the desired reference orbit: various perturbations that aren't modeled in the reference orbit push the actual orbit away from the reference orbit in inertial space, and other perturbations push the Earth and the Earth-relative reference orbit away from the modeled actual orbit in inertial space.

If any particular perturbation is the same from one NISAR repeat cycle to the next, then it generally makes sense to include it in the generation of the reference orbit. For example, since the reference orbit is supposed to repeat with respect to the ground, it will experience the same mean gravity field on each cycle (omitting time-variations such as tidal changes). So a mean gravity field for Earth should be included to high enough degree and order to capture all significant effects on the orbit. On the other hand, perturbations that change from cycle to cycle, such as lunar tidal forces for example, can't be included in the reference orbit.

In the following sections, we examine each perturbation to determine the size of its effect and its repeatability from repeat cycle to repeat cycle. Only repeatable perturbations that cause at least a few meters in position difference are necessarily modeled for inclusion when the reference orbit is generated. Smaller repeatable perturbations may be included as well when doing so seems reasonable. We begin by considering perturbations on the orientation of the Earth.

FRAMING THE EARTH

The Earth is most obviously spinning around an axis, but the spin rate varies and the location of the spin axis changes, both in space and with respect to the crust of the Earth. In some coordinate frames the Z-axis is the spin axis; in others, the Z-axis is the Earth's cartographic pole, which is the point on the Earth at 90 deg north latitude in International Terrestrial Reference Frame (ITRF) coordinates. Thus it is a fixed direction tied to the Earth's crust that stays very close to the spin axis. The motion of the spin axis with respect to the cartographic pole is called polar motion and is small compared to the motion of the spin axis itself in space. (Note that when the spin axis is the Z-axis of an Earth frame, it is often called a "pole" for Earth; usage depends on context. We'll try to be clear in this paper by specifying cartographic pole vs. spin axis.)

Motion of the Earth's spin axis parallel to the NISAR orbit plane does not affect our position in the tube significantly, the very small effect on the nodal period being negligible. But motion of the spin axis either toward or away from the orbit plane directly affects the inclination of the NISAR orbit with respect to the Earth's crust, which affects the orbit position in the diamond at high latitudes (north and south). The spin of the Earth itself affects NISAR's position in the diamond at low latitudes.

Precession

The largest motion of the Earth's spin axis is precession, which is always toward the vernal equinox and is about 0.00557 deg of arc per year, or 0.00018 deg of arc per repeat cycle. This corresponds to about 620 m per year at the Earth's radius, or 20 m per repeat cycle, and at the NISAR altitude to about 680 m per year or 22 m per repeat cycle. This is a relatively small perturbation in an individual repeat cycle, but it is cumulative since the precession is basically in one direction for the mission duration. Precession tips the Earth's spin axis toward the vernal equinox, which itself changes very slowly in direction (taking about 25,700 years to go around the Earth), which is the cause of the very slight curve in the pole direction plot in Figure 1). On the other hand, the NISAR orbit being sun-synchronous with an ascending node at 6 PM, the precession direction cycles around with respect to the orbit plane so that the spin axis moves toward or away from the orbit plane around the equinoxes and parallel to it around the solstices. This results in an annual oscillation in the inclination (assuming no change in the orbit plane in space other than precession around the spin axis for sun-synchronicity) with an amplitude of about 170 m at the NISAR altitude. Since the effect on the Earth-relative inclination changes from repeat cycle to repeat cycle, precession cannot be included when generating the reference orbit.

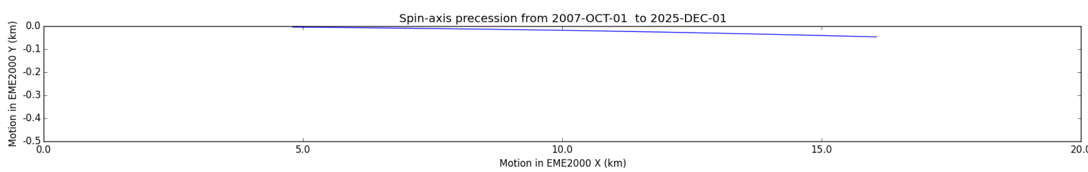


Figure 1. Motion of the spin axis of the Earth for an 18-year time period, shown as an Earth-radius vector projected onto the EME2000 equatorial plane. Note that the Y-axis scale is exaggerated with respect to the X-axis scale (both are in kilometers).

Nutation

In addition to precession, the Earth's spin axis nutates, i.e., wobbles around with respect to the average spin axis (whose motion in space is just precession). This motion is shown in Figure 2. The direction of this motion is variable on several time scales, though generally much smaller than precession. To see how this affects the relationship between the Earth and the orbit, Figure 3 shows how much the spin axis moves toward or away from the orbit plane in 12 days, the duration of the repeat cycle.

For comparison, an angle of 0.0001 deg corresponds to about 11 m at Earth's radius and about 12 m at NISAR's altitude. The variations are not regular or commensurate with the repeat cycle so they cannot be included in the reference orbit, but they are not very large so their absence is acceptable.

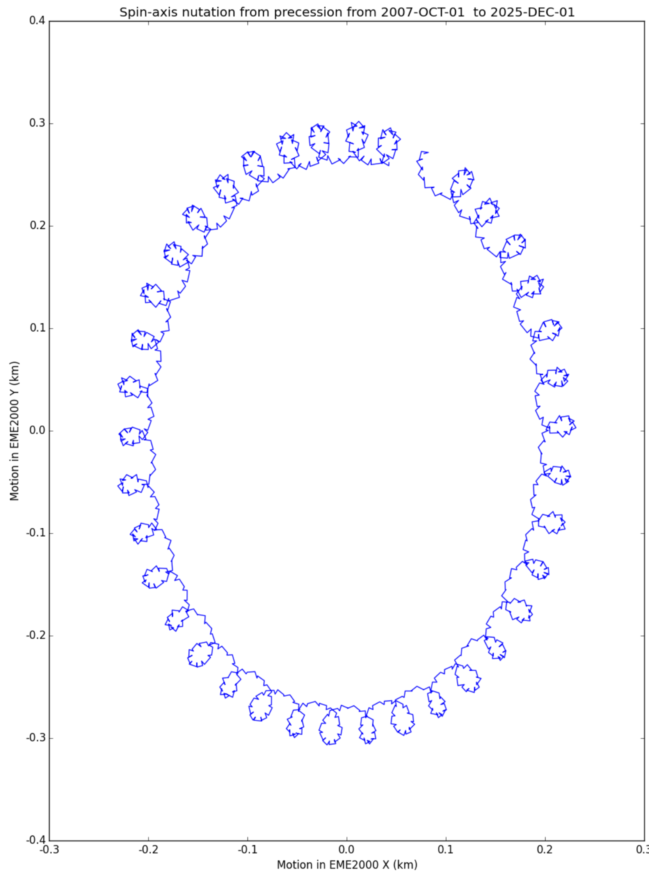


Figure 2. The nutating spin axis with respect to the precessing spin axis. Shown as the difference between Earth-radius vectors projected onto the EME2000 equatorial plane. The basic motion is clockwise.

Polar motion

The position of the Earth's spin axis on the fixed Earth changes and makes a roughly circular pattern. Every 412 days it circulates with a radius of about 3 m to 7 m around a point along the 86 deg meridian which has drifted from about 6 m from the cartographic pole in 1962 to about 11 m from the cartographic pole now, as can be seen by plotting the polar motion position as a function of time from the EOP or EOP2 file. There is a very good animation of this motion on YouTube.*

The motion of the cartographic pole as the Earth spins around the spin axis will give a daily oscillation in inclination, resulting in a daily cross track oscillation of between 6 m and 18 m measured at the highest latitudes. Since the phase of this daily oscillation will vary significantly through the year, it would be impractical to try to model this in the reference orbit. This is a noticeable but tolerable source of noise in the NISAR position in the diamond around the orbit.

*`https://youtu.be/qGBRF_CirHo`

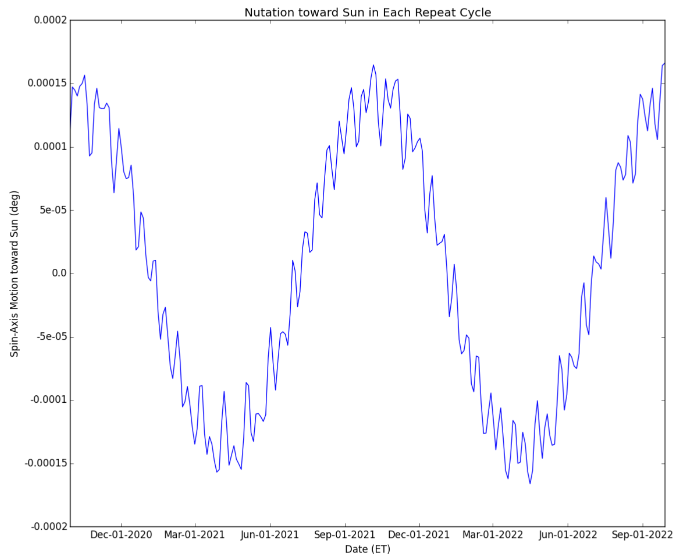


Figure 3. A time history of the difference between the angle of the spin axis to the Sun and the same angle twelve days later.

Variations in spin rate

The spin rate of Earth is not constant (see Figure 4) and can cumulatively add up to a shift in UT (which measures the angle of the Earth relative to a mean Sun) relative to ET (ephemeris time, a uniform time scale for modeling dynamics) on the order of half a second in a year (on average), which corresponds to about 260 m (= 0.5 s * 7125000. m * 366.25/365.25*2*pi rad/day / 86400 s/day) at NISAR's altitude in a year, or about 8.5 m per repeat cycle. This average shift in the Earth's spin rate is included in the model for Earth's orientation that is used in the generation of the reference orbit. (Note that the resulting spin rate for the Earth is the same as in the standard model for approximating Earth's orientation.[5]) The variations in the actual spin rate relative to this average are not included in the reference orbit as their effects are much smaller, especially compared to the effect of drag on the orbit, and they can be corrected as needed without any special consideration during the drag-make-up-maneuver design process, which will be robust to such noise.

PERTURBATIONS ON THE ORBIT

The NISAR orbit is dominated by the central gravity of Earth, which means we can think of it as a Keplerian orbit that osculates because of perturbations. The osculations that are caused by perturbations that we choose to include in generating the reference orbit are captured in the ephemeris, which gives a time history of Cartesian states in space with respect to the Earth. Other perturbations show up as Cartesian position differences between the reference orbit and the actual NISAR orbit (which itself is represented by a model that estimates what will happen in the physical universe).

Perturbations which we include in generating the reference orbit include a 180 x 180 gravity field with fixed solid Earth tide included. Perturbations which we could include are the tidal force and radiation pressure of a mean Sun, which are analyzed below. Whether we want to include these

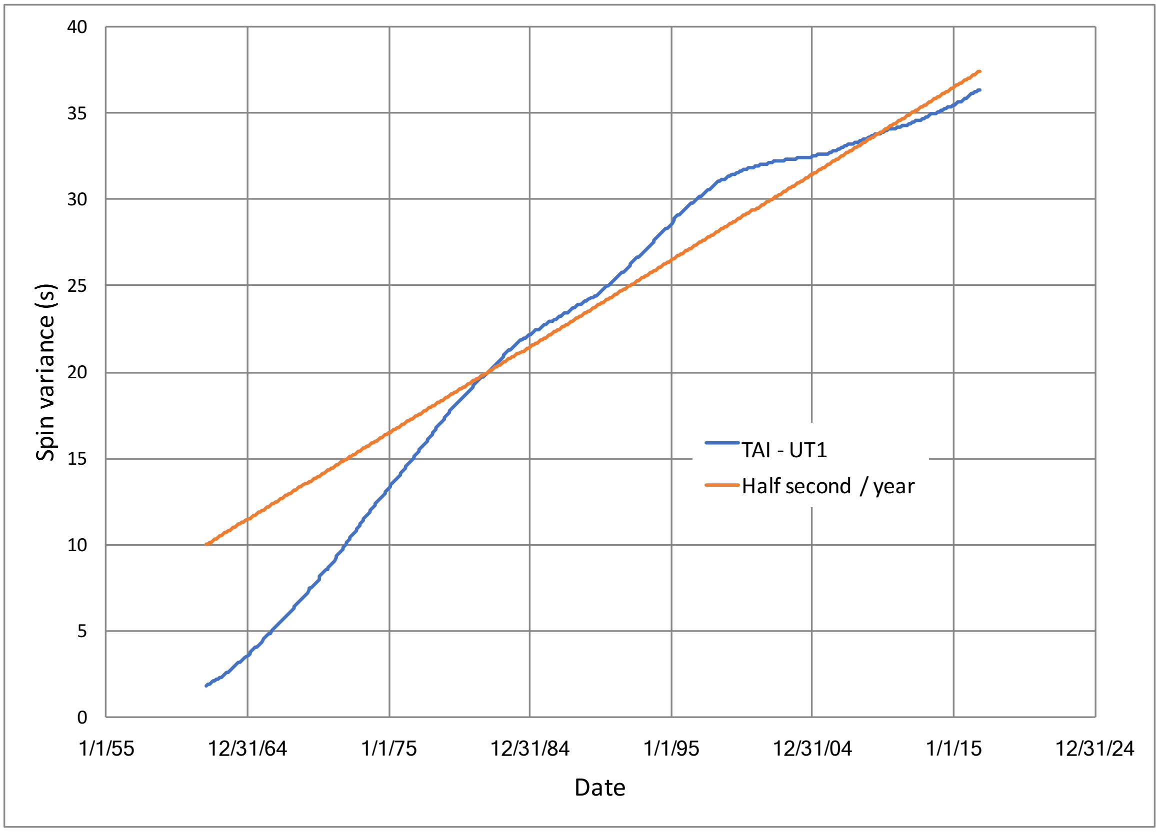


Figure 4. Earth's spin position difference due to changing spin rate, as a function of modified Julian date from 1962-January to 2015-November, compared to the difference that corresponds to one leap second every two years. (TAI is International Atomic Time and has a constant offset from ephemeris time; UT1 is the standard realization of UT.)

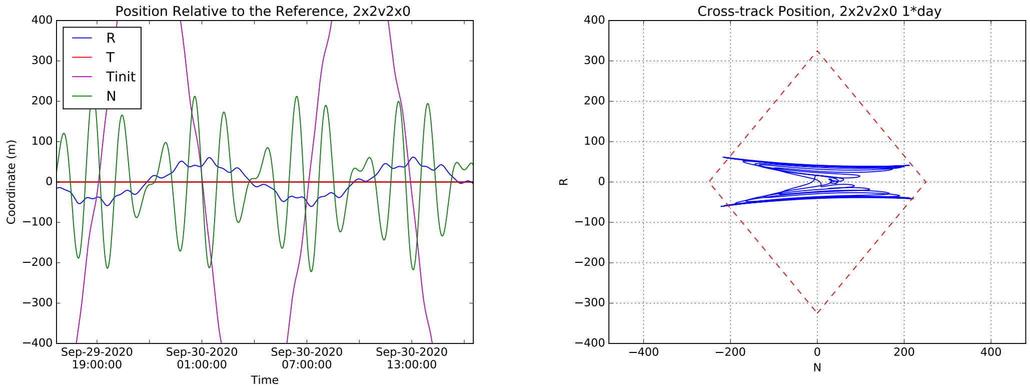
depends on how much trouble it would be to do so and on how big they are.

Gravity field high-order terms

The Earth's gravity field variations are by far the dominant perturbations on the orbit, and of these the dominant variation is that of J2, basically the increased gravity over low latitudes because of the equatorial bulge caused by Earth's spin. We can see the effect of these perturbations by using the JPL software OSMEAN[6,7*] to convert from a fixed set of mean conic orbit elements to initial conditions in a variety of gravity fields and make apple-to-apple comparisons among day-long perturbations. OSMEAN is based on Kaula's theory,[8] except that the J2 conversion uses Alex Konopliv's third order J2 theory.[9] The set of mean elements used here is semi-major axis = 7125.460 km, eccentricity = 0.0011695, inclination = 98.4059 deg, longitude of node = -81.097 deg, argument of periapse = 90.333 deg, and true anomaly = -90.328 deg in Earth-true-equator-and-equinox coordinates at an epoch of 2020-Sep-29T16:39:53 UTC (assuming 36 leap seconds in 2020).

In order to see the effect of different degrees and orders of the gravity field, we consider them in increasing chunks, starting from the smallest subset of the model, which contains just J2, all

*`https://ntrs.nasa.gov/search.jsp?R=19940000681`



(a)

(b)

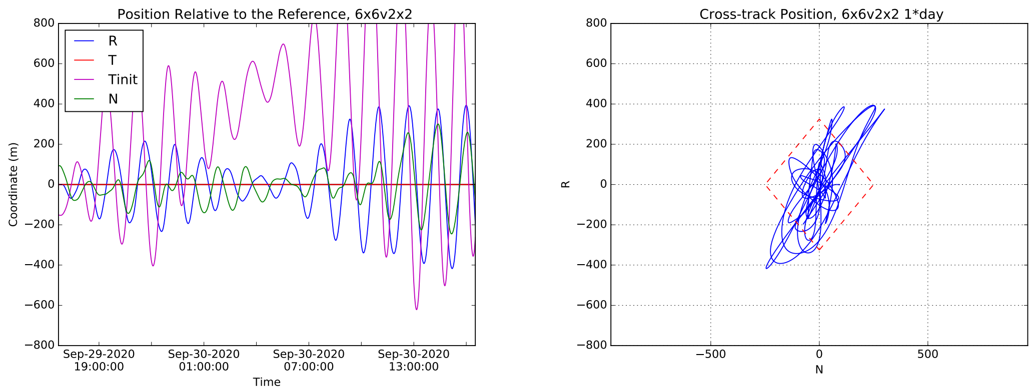
Figure 5. The difference between propagations of given mean orbit in a 2 x 2 gravity field and in a 2 x 0 gravity field (i.e., J2 only) is shown in RTN (radial-transverse-normal) coordinates both as a function of time and in the N-R plane, where all cross track differences are calculated for equal arguments of latitude.

the way up to a high-resolution 180 x 180 field. Generally, the higher the degree and order, the smaller the effect on the orbit. The gravity fields used are all truncations of the GGM02C gravity field. Conversions between mean elements and osculating elements were done with the same gravity field used in the propagation, except that for gravity fields larger than 50 x 50 in degree and order, conversions between mean and osculating elements were done with a field truncated to 50 x 50 because OSMEAN becomes numerically unstable as the field it uses becomes larger than that.

The Earth's oblateness, as given by J2, causes the entire orbit to shift upward between 3 km (over the poles) to 6 km (over the equator) and gives a cross track shift of about 500 m because of an inclination shift at high latitudes. There are also secular shifts of the longitude of the ascending node and the argument of periapse of about $+1$ deg/day and -3 deg/day respectively.

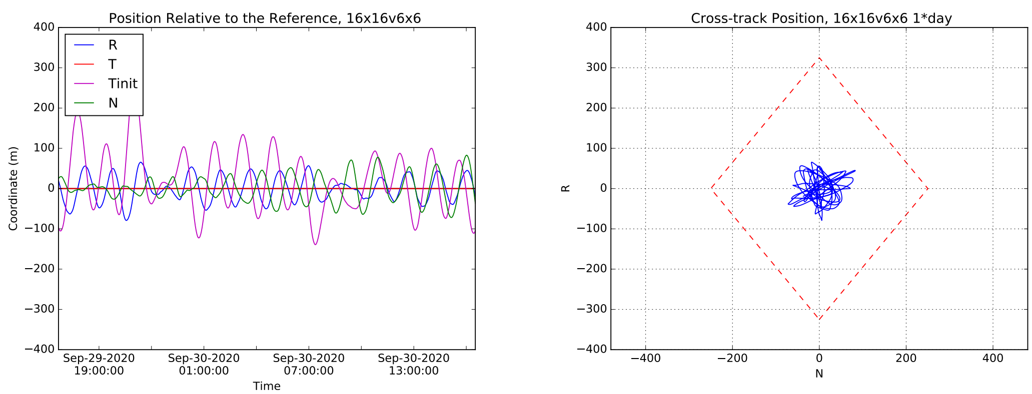
Going to a 2 x 2 gravity field adds cross track and along track perturbations as shown in Figure 5(a); these are visualized relative to the NISAR control diamond in Figure 5(b) where the center of the diamond is along the 2 x 0 propagated orbit. In both figures the ephemeris times are adjusted to remove the along track difference between the orbits so that the cross track comparison is made as a function of argument of latitude.

Going to a 6 x 6 gravity field from 2 x 2 adds somewhat larger perturbations, as shown in Figure 6. Then going to a 16 x 16 gravity field the perturbations are much smaller but still large in the context of the control diamond, as seen in Figure 7. When we expand to a 50 x 50 gravity field the perturbations are small enough that we need to change our scale of plotting to see what is going on in Figure 8. Above the 50 x 50 gravity field the perturbations are so small that we need to expand the scale again in Figure 9, which compares a 150 x 150 gravity field with 50 x 50. These perturbations are small enough to ignore since they amount to a small fraction of a meter position variation over the course of a day and only a couple of meters over a complete repeat cycle, which is much less than the effect of other perturbations on the actual orbit and negligible relative to the size of our reference diamond. We could reasonably use a 36 x 36 gravity field for the NISAR reference trajectory (see Figure 10), but a 50 x 50 gravity field does not take that much longer to propagate in; consequently the 50 x 50 gravity field is recommended. Figure 11 shows the difference over a



(a) (b)

Figure 6. Comparison of propagations in 6 x 6 and 2 x 2 gravity fields.



(a) (b)

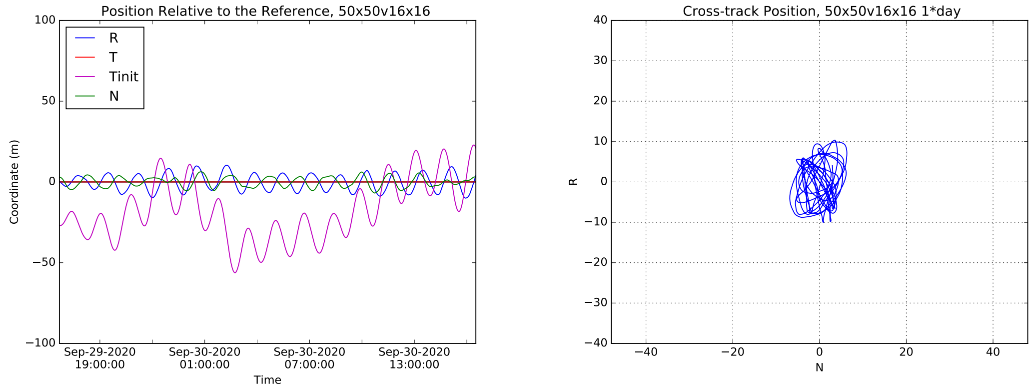
Figure 7. Comparison of propagations in 16 x 16 and 6 x 6 gravity fields.

twelve day propagation between using a 150 x 150 gravity field and a 50 x 50 gravity field.

Mean solar tidal force effects

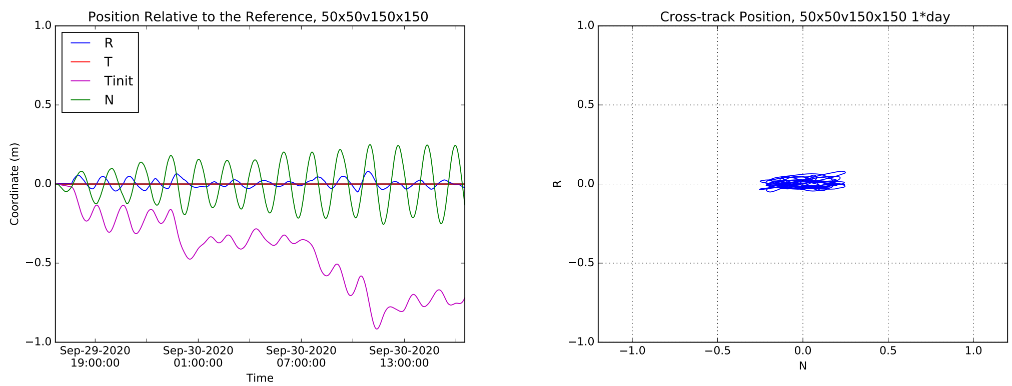
Having the Sun nearly face on to the NISAR orbit all the time has two effects on the orbit: the inward force of the differential solar gravity in the plane perpendicular to the Earth-Sun line means that the period is shorter than the Earth's gravity alone would have dictated; the 8.2 deg tilt of the orbit plane toward the Sun in the north means that the component of the differential solar gravity parallel to the Earth-Sun line in the high-latitude portions of the orbit causes an increase in the precession rate of the orbit beyond what the Earth's gravity field (primarily the J2 component) alone would have dictated.

The inward solar tide amounts to about 0.28 μm/s^2 additional acceleration toward the center of the Earth, which would effectively change the period of the NISAR orbit by about 0.1 ms, equivalent to an altitude change of centimeters. Therefore the mean solar tide force can be ignored when developing the reference orbit.



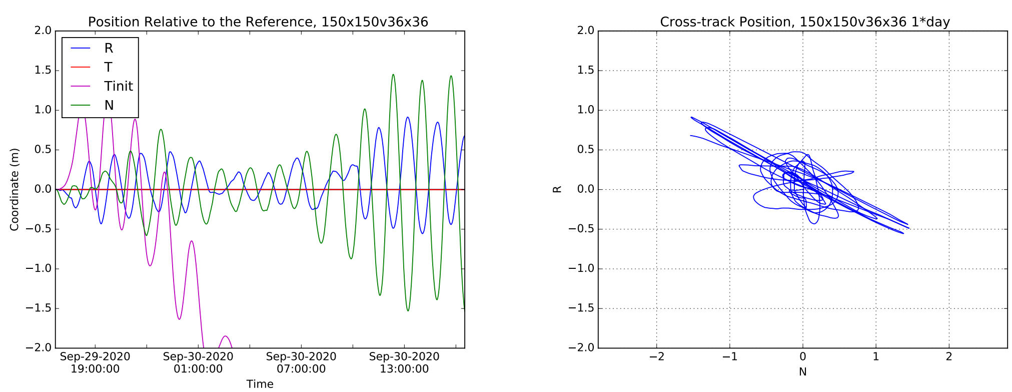
(a) (b)

Figure 8. Comparison of propagations in 50 x 50 and 16 x 16 gravity fields.



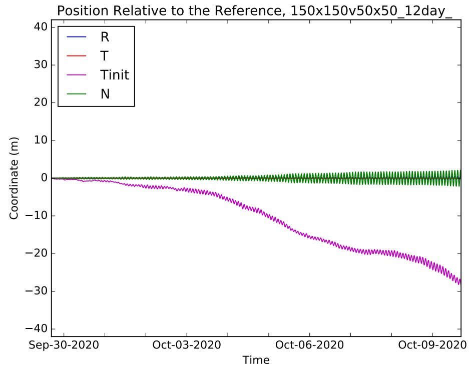
(a) (b)

Figure 9. Comparison of propagations in 150 x 150 and 50 x 50 gravity fields. The gravity terms above 50 in degree and order contribute a small fraction of a meter.

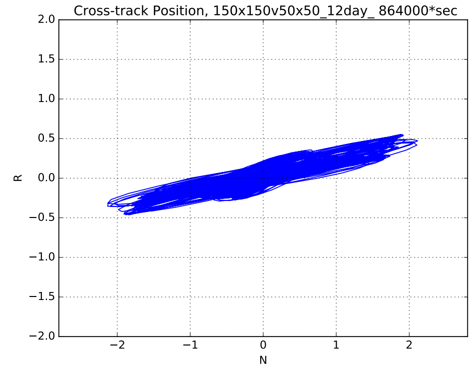


(a) (b)

Figure 10. Comparison of propagations in 150 x 150 and 36 x 36 gravity fields. The residuals are about 3 times greater than in Figure 9.



(a)



(b)

Figure 11. Comparison of propagations in 150 x 150 and 50 x 50 gravity fields for a 12-day propagation.

The increase in the precession rate is harder to calculate. The cross track acceleration due to solar tide at the highest latitudes is about 0.082 μm/s^2 and its effect on the ascending node is reduced by $\sin^2(\phi)$ at other latitudes , which integrates out to a total ΔV of 0.25 mm/s (= 0.082 μm/s^2 * (1/2) * 5993 s) per orbit toward node change, or 0.00033 deg (= 0.00025 m/s / 7480 m/s * 180 / pi *173) per repeat cycle. The lunar tide cross track acceleration at the highest latitude when the orbit is about face-on to the Moon is twice as high as the Sun's, but the total effect is reduced because the Moon goes around the Earth every month; it would be reasonable to estimate the Moon's effect on precession to be roughly the same as the Sun's. The precession rate difference between the reference orbit and an orbit propagated with the Sun and Moon on has been measured and an average increase of 0.0235 deg per year was found, which is 0.00077 deg per repeat cycle. So theory and simulation agree pretty well. Either way this effect on the sideways position in the diamond at the equator is equivalent to an altitude change less than a millimeter and again can be ignored.

Solar radiation pressure

Solar radiation pressure on a fully reflective plate in Earth orbit is about 9 μN/m^2, which is an acceleration on NISAR of at most 0.09 μm/s^2. Because NISAR's orbit is sun-synchronous and face-on to the Sun on average, most of the force is trying to push the orbit plane off center and would offset the orbit plane by no more than 0.1 mm (= 90e-9 m/s / 7.852 m/s * 7125000 m), an insignificant amount.

As much as 50% of the solar radiation force might be in the orbit plane at different times when the true Sun is maximally away from the fictitious mean Sun (i.e., at a solstice) and over a 12-day cycle this would amount to about 5 cm/s ΔV. The effect is comparable to that of drag except that it is not in a constant direction with respect to the velocity vector so it would average out to nearly a zero effect on semi-major axis. The effect on the eccentricity vector would be less than 0.00001 but is in varying directions from cycle to cycle, so we can't include this in the reference orbit.

Perturbations not included in the reference orbit

Many forces are effectively random with respect to their sequential effects on the orbit from one repeat cycle to the next. These include the difference between the true Sun's and the mean Sun's tidal force and radiation pressure, the lunar tidal force (except for the constant solid Earth tide), small forces, corrections to all those due to relativiity, and everything else in the universe.

RECOMMENDATIONS FOR THE REFERENCE AND ACTUAL ORBIT MODELS

For the reference orbit we use a model for the Earth that has a fixed pole and a constant rotation rate. We use a 180 x 180 model of the Earth's gravity field, but do not include any other perturbations (except for relativistic corrections to Earth's gravity parameter, which are constant and are included in our propagation software by default and with no detectable effect on computer performance). Although the terms in the gravity field model above 50 x 50 introduce only small variations in the orbit, the reference orbit will not need to be generated often and the cost of the additional gravity field calculations is tolerable.

In preparation for and use in mission operations, we need to be able to measure and predict where the spacecraft is with respect to the reference orbit. We would like to do this with a precision of better than 1% of the reference diamond, and with comparable accuracy to the extent our knowledge allows (unfortunately, we are unable to predict solar activity and the resulting variation in atmospheric density well enough to do this consistently–errors in drag predictions can result in tens of meters in cross track error). To model the actual orbit we should use a model for Earth's motion from the International Earth Rotation and Reference Systems Service (IERS)—specifically the International Terrestrial Reference Frame (we have been using ITRF2008 in mission design analyses so far, but later realizations of the ITRF are not expected to shift the reference orbit in space by more than about a meter, a negligible amount), an Earth gravity model that is at least 50 x 50, and external perturbations such as the differential gravities (differenced between the pull on the spacecraft and the pull on the Earth) of at least the Sun and Moon, and drag. Smaller perturbations include the time-varying adjustments to the Earth gravity field model due to solid Earth and ocean tides, solar radiation pressure (which are comparable in magnitude), and the effect of Earth's albedo (which is even smaller); these are still being investigated as to whether they need to be included.

DESIGNING THE REFERENCE SCIENCE ORBIT (RSO)

Now that we have the dynamics in hand, we need to find the parameters of the reference science orbit that meet the constraints of the mission. The RSO is the fiducial reference that the Observatory will "fly-back" to and defines the center of the required Diamond defined by the science measurements; some other missions refer to this trajectory as the "virtual" spacecraft. The first part of this process is to choose the general parameters that are acceptable to science, in particular the time scale of the repeat cycle, and the altitude of the orbit.

Figure 12 indicates sun-synchronous repeat-ground track-candidate orbits between 500 km and 1,000 km altitude with cycle lengths between 1 and 21 days. Each dot represents a sun-synchronous, frozen, repeat-ground-track orbit. Green dots indicate orbits with positive swath overlap at the equator of 20 km or more; red dots indicate orbits with gaps at the equator (any color other than green or red indicate various swath overlaps between 0 km and 20 km). The pink circle indicates the candidate orbit that the NISAR project has selected for its baseline 173-orbit, 12-day repeat ground track orbit.

The selected repeat ground track is the only option with the desired 12-day repeat cycle that is in the required altitude range with positive but not excessive radar swath overlap for the instruments' likely modes of operation. Higher altitudes would result in unacceptably low signal-to-noise ratio

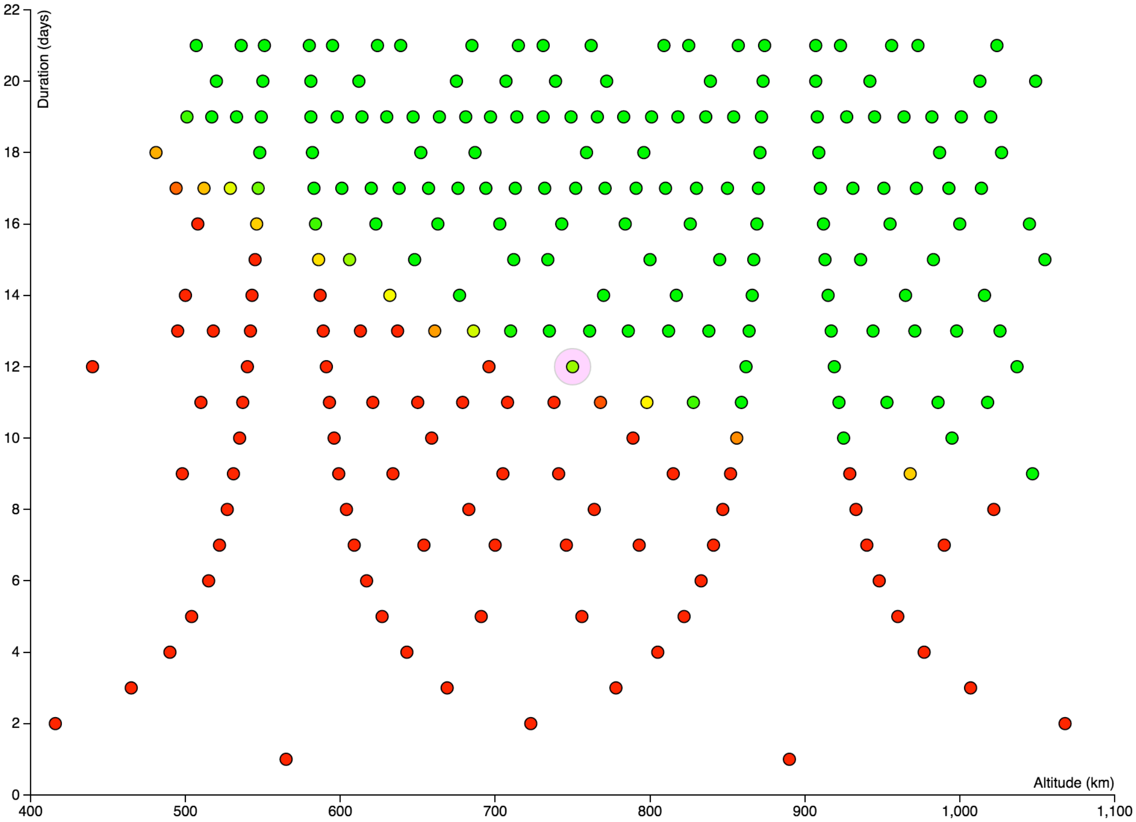


Figure 12. Sun-Synchronous Repeat Ground Track Trade Space.

(SNR) for the radar instruments, whereas lower altitudes would have unacceptably high drag, resulting in orbital trim maneuvers occurring too frequently, interfering with science observations and driving operations costs.

Given the choice of the 12-day, 173-orbit RSO and the models described earlier in this paper, a fully-integrated trajectory was created using a utility (called RepeatOrbit) in the Monte[10,11] toolset that computes the initial osculating state for any combination of repeat-ground-track (RGT), sun-synchronous, and/or frozen orbital conditions. This utility implements an algorithm similar to the one described by Russell and Mara.[12]

The RepeatOrbit utility uses an orbit propagator defined by the user, who thus controls the models included, to find initial conditions which give a repeat orbit with the specified number of revolutions (173 for NISAR). It does so by using an internal optimizer to vary the initial state in order to minimize the differences in certain state parameters between the initial and final states. The final state is the state when the propagation completes the specified number of revolutions (determined by counting the number of passes through the ascending node of the orbit) and attains the same Z position value as it started from, with the same direction of motion.

The differences being minimized ensure that within a user-specified tolerance the orbit gives a continuous repeat ground track and is sun-synchronous and frozen. The total cost function in the optimizer is the sum of the scaled magnitudes of the differences, where the user specifies the scale factors to be used. The control variables in the optimizer are certain elements of the initial state:

semi-major axis, eccentricity, inclination, and argument of periapse.

The repeat-ground-track 'miss distance' is defined by Equation (1). This function is zero when the repeat orbit's ground track ends at the same point it began.

$$Miss_{RGT} = \sqrt{(\Delta lat)^2 + (\Delta lon)^2} \tag{1}$$

The sun-synchronicity 'miss distance' is defined by Equation (2) as the difference of two differences all having to do with values of the mean local time of the ascending node (MLTAN): the first difference is between the MLTAN at the initial state and the desired MLTAN for the NISAR orbit, the second difference is between the MLTAN at the final state and the desired MLTAN per the bracketed portion of following equation. A bias term is added to offset any noise in the MLTAN calculation; this is to ensure that the average MLTAN value remains at the desired value for the full 12-day repeat interval.

$$Miss_{Sun\ Sync} = \Big(|L_1 - L_T| - |L_2 - L_T|\Big) - mltan\_Bias \tag{2}$$

where

$L_1 =$ mean local time of the initial state (which for NISAR has been defined at the 1st ascending node)

$L_2 =$ mean local time at ascending node of the final state (which for NISAR is defined to be at the 173rd subsequent ascending node crossing)

The frozen orbit 'miss distance' is actually defined as two 'miss distance' functions: the first minimizes the difference in spherical radius relative to the central body; the second minimizes the difference in eccentricity. Both differences are between the initial state and final state.

Besides orbit elements used as controls in the optimization that were mentioned above, the remaining orbital elements are set as follows: the longitude of the acending node is set to the appropriate value to achieve the desired MLTAN at the initial state epoch and the argument of latitude is set to zero and not varied, because it is held fixed for calculating the various 'miss distances', as described above. There are no additional explicit constraints levied on the optimization problem.

An initial guess at the initial state definition is given to the optimization problem, and sufficiently small bounds are set on the controls to give enough, but not too much, scope to the optimization search algorithm to find the optimal initial state. For the converged NISAR RSO, the following listing summarizes the inertial state differences between the initial state and final state.

```
Repeat Cycle Timing
---------------------------------------------------------------
First Eq. Crossing          : 28-DEC-2021 00:00:00.000000000 UTC
Number of Orbits            : 173
Repeat Cycle Target (days)  : 12
Repeat Cycle Actual (days)  : 12.0000001322
Repeat Delta-T (sec)        : -0.000475955294377

Lat/Lon/Alt Matching
---------------------------------------------------------------
Longitude Difference (deg)  : -1.26235808196e-07
Latitude Difference (deg)   : -8.20583107818e-12
Altitude Difference (m)     : -4.99562702316e-06

MLTAN Matching
---------------------------------------------------------------
MLTAN @ t1 (MV/SH Alg.)     : 18.0000386572
MLTAN @ t2 (MV/SH Alg.)     : 18.0000380616
MLTAN Difference (sec)      : -0.00214434044921

COE Comparisons (Body-Fixed Inertial)
---------------------------------------------------------------
SMA (km)                    : -2.57465489995e-06
ECC                         : -6.048000208286330e-12
INC (deg)                   : 1.87080226364e-09
NOD (deg)                   : -1.26237042252e-07
ARG (deg)                   : 1.7590373355e-05
AOL (deg)                   : 360.0

Cartesian Comparisons (Body-Fixed Inertial)
---------------------------------------------------------------
X (m)                       : -0.0157120287645
Y (m)                       : 1.44154910231e-06
Z (m)                       : -1.01558829834e-06
dX (m/s)                    : -2.67927902087e-08
dY (m/s)                    : 3.39614952827e-06
dZ (m/s)                    : -1.3652323716e-06
```

The resulting osculating and mean elements for the initial state are given in Table 1.

Once this 12-day, 173-orbit integrated trajectory is defined, it can be thought of as a latitude, longitude, and altitude profile defined relative to the surface of the Earth as shown as the magenta line in Figure 13. To create a continuous ephemeris for the entirety of the expected 3-year science mission

Table 1. Osculating and mean elements in Earth-true-equator-and-equinox coordinates for the initial state of the RSO.

	Osculating Elements	Mean Elements
Semi-Major Axis (km)	7134.57364	7125.48649
Eccentricity	0.0012501	0.0011653
Inclination (deg)	98.39906	98.40593
Longitude of Node (deg)	6.69088	6.69016
Argument of Periapsis (deg)	68.93115	90.09259
True Anomaly (deg)	−68.93105	−90.09652

(approximately 100 cycles), a procedure was developed to replicate this latitude/longitude/altitude profile for the entire span from the expected launch date of December 28, 2021 to 2024. This ephemeris defines the center of the diamond for all times of interest.

SHARING THE REFERENCE ORBIT

To disseminate the RSO, we use the interfaces defined by NASA's Navigation and Ancillary Information Facility (NAIF) in their observation geometry information system named "SPICE". A Spacecraft and Planetary Kernel (SPK) file contains ephemeris (trajectory) data for "ephemeris objects" such as spacecraft, Sun, Earth, rover, ground station, planet barycenter, etc. SPK files are written in a binary format denoted by the ".bsp" file extension, are not human-readable, and are commonly accessed using SPICE utilities and libraries that are available on line.*

Due to the potential differences in implementations/formulations of the High-Precision Earth-Fixed frame in various software toolsets used throughout the NISAR team, it was determined that the NISAR ephemeris would be written as an SPK file relative to the ITRF93 Earth-Fixed frame that is built in to the SPICE toolkit—if the states were written in some inertial frame (in this case EME2000) the relationship between the intended Earth-relative latitude/longitude/altitude and the EME2000 inertial frame would be lost. To say it another way, a user could read in the EME2000 states, but would inadvertently calculate a different latitude/longitude/altitude profile relative to the Earth's crust as defined in their software.

Therefore, in order to translate the earth-relative states as specified in the SPK (as indicated by using SPICE frame 13000), a user would need the following additional SPICE kernel files (with definitions from the on-line documentation):

- Planetary Constants Kernel (PCK)—provides cartographic and physical constants data for Solar System bodies. SPICE software uses these data when determining observation geometry dependent on the size, shape, and orientation of planets, natural satellites, comets, and asteroids. For example, earth_070425_370426_predict.bpc is the currently-available low accuracy, long term predict kernel. The extended predict region of this kernel—the time interval following the end of the predict region of the input EOP file—does not estimate UT1-TAI or polar motion. For the timeframe of the NISAR mission, a new predict kernel was developed to span 2017 to 2027.

- The planetary ephemeris (de430.bsp)—provides the positions of all the planets in the solar system.

*https://naif.jpl.nasa.gov/naif/

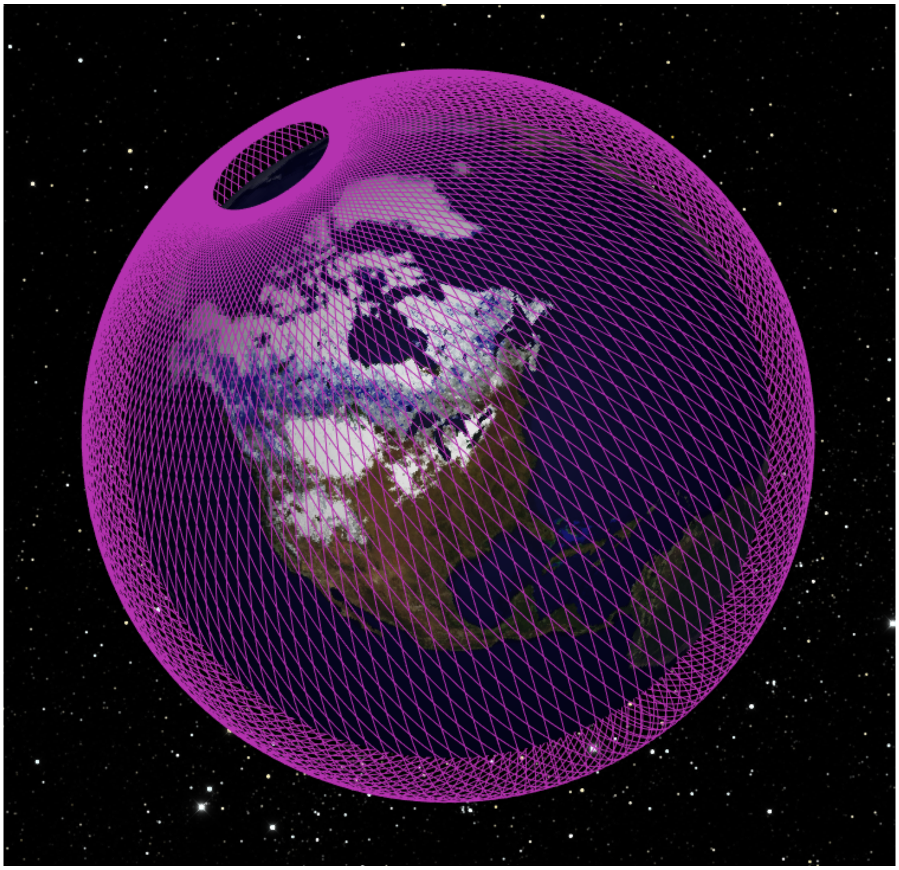


Figure 13. Orbits of the RSO with respect to the body of the Earth.

- The leap seconds kernel (naif0012.tls)—provides all the currently-defined leap seconds.
- The earth-fixed frame kernel (earth_fixed.tf)—This is a kernel used to map the reference frame alias EARTH_FIXED to a specific reference frame. For the NISAR case, the user has to update the text in this file to include the 'ITRF93' name instead of 'IAU_EARTH'.
- The earth body-fixed reference frame body association file (earth_assoc_itrf93.tf)—This kernel must be loaded together with a binary Earth PCK. When this kernel is loaded it will indicate that the ITRF93 frame is associated with the Earth.

Because many of the NISAR team use STK, a set of Earth-orientation and leap second files were created in accordance with the STK format(s) and are consistent with the aforementioned SPICE kernel files.

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REFERENCES

[1] O. Alvarez-Salazar, S. Hatch, J. Rocca, P. Rosen, S. Shaffer, Y. Shen, T. Sweetser, and P. Xaypraseuth, "Mission design for NISAR repeat-pass Interferometric SAR," *Proc. SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII, 92410C*, 2014, 10.1117/12.2074162.

[2] T. H. Sweetser, M. A. Vincent, and S. J. Hatch, "Shootin'the Pipe around the World: Orbit Design and Maintenance for L-Band SAR Radar Interferometry," *AIAA/AAS Astrodynamics Specialist Conference*, No. Paper 2014-4117, AIAA, 2014.

[3] S. D'Amico, C. Arbinger, M. Kirschner, and S. Campagnola, "Generation of an optimum target trajectory for the TerraSAR-X repeat observation satellite," *18th International Symposium on Space Flight Dynamics*, Vol. 548, 2004, p. 137.

[4] Y. Arikawa, T. Yamamoto, Y. Kondoh, K. Akiyama, H. Itoh, and S. Suzuki, "ALOS-2 orbit control and determination," *Geoscience and Remote Sensing Symposium (IGARSS), 2014 IEEE International*, IEEE, 2014, pp. 3415–3417.

[5] B. A. Archinal, M. F. A'Hearn, E. Bowell, A. Conrad, G. J. Consolmagno, R. Courtin, T. Fukushima, D. Hestroffer, J. L. Hilton, G. A. Krasinsky, *et al.*, "Report of the IAU working group on cartographic coordinates and rotational elements: 2009," *Celestial Mechanics and Dynamical Astronomy*, Vol. 109, No. 2, 2011, pp. 101–135.

[6] J. R. Guinn, R. S. Bhat, M. A. Vincent, and A. S. Konopliv, "Conversion Of Classical Orbital Elements," NASA Tech Brief NPO-18741, NASA, 1994.

[7] J. R. Guinn, "Periodic Gravitational Perturbations for Conversion Between Osculating and Mean Orbit Elements," *AAS/AIAA Astrodynamics Conference 1991* (B. Kaufman, K. T. Alfriend, R. L. Roehrich, and R. R. Dasenbrock, eds.), Vol. 76 of *Advances in the Astronautical Sciences Series*, San Diego, Univelt, Inc., 1992, p. 1470 and microfiche supplement.

[8] W. M. Kaula, *Theory of Satellite Geodesy*. Blaisdell Publishing Co., dover 2013 ed., 1966.

[9] A. Konopliv, "A perturbation method and some applications," *Celestial Mechanics and Dynamical Astronomy*, Vol. 47, No. 4, 1989, pp. 305–320.

[10] S. Evans, W. Taber, T. Drain, J. Smith, H.-C. Wu, M. Guevara, R. Sunseri, and J. Evans, "Monte: the next generation of mission design & navigation software," *The 6th International Conference on Astrodynamics Tools and Techniques (ICATT), International Conference on Astrodynamics Tools and Techniques, Darmstadt, Germany*, 2016.

[11] J. Smith, W. Taber, T. Drain, S. Evans, J. Evans, M. Guevara, W. Schulze, R. Sunseri, and H.-C. Wu, "MONTE Python for Deep Space Navigation," *Proceedings of the 15th Python in Science Conference (Scipy 2016)* (S. Benthall and S. Rostrup, eds.), 2016, pp. 62 – 68.

[12] R. P. Russell and M. Lara, "'Repeat Ground Track Lunar Orbits in the Full-Potential Plus Third-Body Problem," *AAS/AIAA Astrodynamics Specialists Conference*, No. AIAA-2006-6750, AIAA, 2006.